N84-22567

NASA Technical Memorandum 83615

Experimental Investigation of the Low NO_x Vortex Airblast Annular Combustor

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Prepared for the
Twentieth Joint Propulsion Conference
cosponsored by the AIAA, ASME, and SAE
Cincinnati, Ohio June 11-13, 1984

NASA

EXPERIMENTAL INVESTIGATION OF THE LOW NO_x VORTEX AIRBLAST ANNULAR COMBUSTOR

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E-2046

Abstract

A low oxides of nitrogen vortex airblast annular combustor has been evaluated which has attained the goal of 1 gm NO_2/kg fuel or less during operation. The experimental combustor test conditions were a nominal inlet-air temperature of 703 K, inlet total pressures between 0.52 to 0.83 MPa, and a constant inlet Mach number of 0.26. Exit temperature pattern factors for all test points were between 0.16 and 0.20 and exit swirl flow angles were 47 degrees at isothermal conditions and 23 degrees during combustion. Oxides of nitrogen did not exceed 1.05 gm NO_2/kg fuel at the highest inlet pressure and exhaust temperature tested. Previous correlations have related NO_x proportionally to the combustor inlet pressure raised to some exponent. In this experiment, a band of exponents between 0.5 and 1.0 resulted for fuel-air ratios from 0.023 to 0.027 and inlet pressures from 0.52 to 0.83 MPa.

Introduction

The performance characteristics of an experimental combustion system are reported for inlet pressures up to 0.83 MPa. Previous contractual efforts tested a can and two annular combustors to evaluate the lean, premixed, low NO_x concept. This paper reports the test results of a full-annular combustor with emphasis on NO_x emission levels in a well mixed reaction zone.

Previous environmental studies have questioned and debated the issue of aircraft gas turbine emissions and the effect these emissions had on the earth's stratosphere.[1,2] The Environmental Protection Agency established and issued emission standards designed to regulate various exhaust pollutants in 1973.[3] Though the emission standards did not include emission levels at cruise condition, a program was initiated by NASA Lewis Research Center with Solar Turbines Incorporated to address this particular question. It was the consensus at this time that gas turbine exhaust pollutants could be reduced and that the technology was available. Therefore the "Advanced Low NO_x Combustors for Supersonic High-Altitude Aircraft Gas Turbines" program was conceived with a goal to attain NO_x values below 1 gm NO_2/kg fuel at cruise condition. Due to promising low NO_x level results, two follow-on contracts were added to the effort.

Several combustor concepts were evaluated in the three-separate contracts during the low NO_x program, but the Vortex Airblast (VAB) combustor proved to be the most promising. To facilitate experimental modifications, the initially contracted VAB experimental combustor concept was a small-scale can combustor, 0.127 m (5 in.) in diameter. Inlet test conditions were temperatures between 756 to 830 K, pressures of 0.200 and 0.494 MPa, and airflow rates of 0.392 kg/s at low pressure and 0.916 kg/s at the higher pressure. By the end of this contract, the combustor had demonstrated the capability of meeting the NO_x goal of 1.0 gm NO_2/kg fuel at cruise condition.[4,5]

The second VAB contract studied combustor operation at idle condition. Four modifications were made to improve combustion efficiency at idle. These included simulated variable geometry (changing inlet swirl angle), variable dilution liner flow, fuel injection techniques and fuel staging. References 6 and 7 discuss this work in more detail describing the varying degrees of success for each technique.

The third VAB contract progressed to an axial-flow, full annular configuration. Preliminary tests were conducted on a small-scale annular combustor 0.216 m (8.5 in.) in diameter to make a smoother design transition between the can and full-scale annular combustor. The small-scale annular combustor was tested at limited idle and cruise conditions. See reference 7 for the combustor design description and test results. Once the combustor design was established and the results were acceptable, the full-scale annular combustor phase was initiated. This combustor was 0.66 m (26 in.) in diameter and tested only at atmospheric pressure. Test conditions were simulated idle (T_{in} = 422 K) and cruise conditions (T_{in} = 785 to 826 K) using several different fuel injection techniques.[8] The results from these tests then created a baseline for the NASA Lewis tests that would be conducted at higher inlet pressures.

This paper presents the results obtained with the full-scale annular VAB combustor[8] at inlet pressures between 0.52 and 0.83 MPa. The inlet temperature and inlet Mach number were nominally 703 K and 0.26, respectively. Reference velocity was maintained at 16.1 m/sec while the fuel-air ratio was varied from 0.023 to 0.027 using Jet-A fuel.

Apparatus and Procedure

Test Facility

A schematic of the test facility is shown in figure 1. A natural gas preheater was used to heat the combustor inlet air indirectly to the desired 703 K. Air was supplied by the Center's air system with a maximum test flow rate of 16.7 kg/sec and a range of total inlet pressure from 0.52 to 0.83 MPa. The city water system supplied quench water to the combustor exhaust system. Reference 9 gives a more detailed description of the test facility.

Combustor

A cross-section of the VAB combustor is shown in figure 2. Forty swirl vanes are located at the combustor inlet and oriented at a 60 degree angle

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from the axial centerline. The swirl vanes established a full rotational swirl flow inside of the combustor that caused enhanced mixing. Fuel was introduced into the combustor using forty, eight-point counterflow injection tubes located between each swirl vane. Each injection tube was 0.3175 cm (0.125 in.) in diameter with eight orifices 0.0381 cm (0.015 in.) in diameter, in-line, facing upstream to the airflow. Figure 3 shows the fuel tubes and airfoil-shaped swirl vanes at the combustor inlet. The fuel and air were mixed in the premixed channel and directed into the reaction zone. A torch ignitor located in the reaction zone was used for ignition only and was deactivated once ignition occurred. The inner and outer combustor liners shown in figure 2 used a combination of convective and film cooling techniques developed during the small-scale annular combustor phase. Airflow splits in the combustor were 71.4 percent through the swirler vanes, 10.1 percent for inner liner cooling and 18.5 percent for outer liner cooling. Pressure differential across the combustor was 5.3 percent. The variable dilution air ports were not used in this experiment.

Instrumentation

Rotating instrumentation and the radial traversing yaw probes in the combustor exit plane were all water-cooled. There were three rotating probes each for temperature, gas sampling and pressure for a total of nine probes spaced 40 degrees apart. The set of three thermocouple probes, for example, were spaced 120 degrees apart from each other. The probes were stepped every three degrees and swept 120 degree arcs for exit temperature data collection. A computer was used to step the probes and record the data at each stepped location. Each probe had either five instrumentation ports or thermocouples that were located at five centers of equal annular area.

Exit thermocouples were platinum-plus-13-percent-rhodium vs. platinum and these temperatures were uniquely displayed on a color CRT located in the control room. This CRT was used to monitor the entire exit plane of the combustor to graphically "see" the temperature distributions and to isolate and troubleshoot any hot spots during a run, though this never occurred. Once the reading was taken for the particular test condition, a computer program developed by Lewis showed the local exit temperature variance. This calculation is defined as

$$\text{local temperature variance} = \frac{T_{\text{exit, local}} - T_{\text{exit, average}}}{T_{\text{exit, average}} - T_{\text{inlet, average}}}$$

Nine color blocks were used to indicate local temperature variance values between -0.8 (cold) to +1.0 (hot) in 0.2 increments. Six hundred local exit temperatures were recorded per test reading, in addition, the computer program interpolated between steps and thermocouples to complete the display or "donut" plot.

The gas sampling probe had five ports that were connected to a common manifold that directed the sample gases to the gas analysis equipment located in the control room. The water-cooled probes provided quick quench to freeze the chemical reactions. Sample lines to the gas analysis equipment were steam-heated to prevent condensation of hydrocarbons. Each port of the five port exit pressure probes was individually monitored and isolated from the other port readings.

A single radial traversing angle probe was located 15 degrees counter-clockwise from top dead center looking upstream. It was stepped at five centers of equal area by a computer. A null pressure transducer was used to determine the angle of airflow at the exit plane using two static pressure readings on either side of a total pressure port. When the two static pressure readings were equal, the total pressure port would be facing directly into the airstream. The angular position of the yaw probe was then recorded by a controller that was linked to a computer for digital read-out. This probe was also water-cooled to withstand the combustor exhaust temperatures.

Test Procedure

An inlet temperature of 703 K was maintained for all experimental test conditions, and typically, combustor light-off inlet pressure and Mach number were set at 0.52 MPa and 0.22. The torch ignitor was activated with a fuel-air ratio of 0.020 in the combustor. If ignition did not occur within 30 seconds, the torch ignitor was turned off and the fuel lines were purged with gaseous nitrogen. The combustor could not be operated below a 0.020 fuel-air ratio because of the lean, premixed concept, and no higher than a 0.027 fuel-air ratio due to local liner overheating. Test data were recorded using a real-time mini-computer during the test and an IBM 370 computer to reduce and process the extensive data batch readings.

Results and Discussion

Exit Temperature Pattern

Figure 4 shows a picture of the CRT temperature display during a normal test run. This particular "donut" plot is for a fuel-air ratio of 0.023, and shows evenly distributed exit temperature and uniform mixing profiles with a cooler inner and outer combustor liner. The pattern factor which corresponds to the results shown in figure 4 is 0.16. Pattern factor is defined as

$$\delta = \frac{T_{\text{exit, maximum}} - T_{\text{exit, average}}}{T_{\text{exit, average}} - T_{\text{inlet, average}}}$$

The local temperature variances shown in figure 4 had a range from -0.2 to +0.2. This figure is representative of the 0.16 to 0.20 pattern factors attained in this experiment. Low pattern factors are to be expected due to the many fuel injection points and the thorough mixing in the combustor.

NO_x Emissions

Figure 5 shows NO_x emissions as a function of fuel-air ratio at three inlet pressures. All data used in this figure had combustion efficiencies greater than 99 percent. Figure 5 shows that as fuel-air ratio and inlet pressure were increased, NO_x increased also. The highest NO_x level in this figure is 1.05 gm NO_2/kg fuel at 0.83 MPa and effectively meets the goal of 1.0 gm NO_2/kg fuel set by Solar. Table I lists selected NO_x values by Solar and Lewis for comparison.

References 5 and 7 stated that the VAB combustor didn't exhibit any noticeable pressure effect on NO_x emissions over the ranges tested (0.20 and 0.50 MPa[5]; 0.30 and 0.67 MPa[7]). Reference 10 reported that NO_x increased with pressure to the 0.65 power. In the Lewis experiment, data were taken over a limited range of pressures so that data scatter made precise definition of a pressure exponent difficult. In figure 6, a crossplot of the results from figure 5 does demonstrate the trend of increasing NO_x with pressure. The pressure exponent for this data was estimated to be in the range of 0.5 to 1.0.

Unburned Hydrocarbon and Carbon Monoxide Emissions

The unburned hydrocarbon (UHC) and carbon monoxide (CO) emissions data are presented in figures 7 and 8. In figure 7, UHC was 8.9 gm UHC/kg fuel for an inlet pressure of 0.52 MPa (fuel-air ratio of 0.023, T_{exit} = 1424 K). UHC values decreased when inlet pressures and fuel-air ratios increased. The lowest UHC value attained was 0.85 gm UHC/kg fuel at 0.83 MPa and a fuel-air ratio of 0.027.

CO levels in figure 8 did not exceed 12.37 gm CO/kg fuel at 0.83 MPa (fuel-air ratio of 0.023, T_{exit} = 1426 K). CO levels decreased with decreased inlet pressure and increased fuel-air ratio. The lowest CO value attained was 1.86 gm CO/kg fuel at 0.62 MPa and a fuel-air ratio of 0.027, but it is good assumption that a lower value for CO could have been attained if the combustor could have been operated at a higher exit temperature.

Table I summarizes the emissions data from this experiment and Solar's annular combustor at the same exit temperatures. As shown in the table, the NO_x data obtained with this VAB combustor matches the established trend, i.e., as pressure increases so does NO_x. UHC at T_{exit} = 1424 K follow the trend of decreased UHC with increased inlet pressure. The UHC were essentially constant at 1539 K. With the CO data, the trend indicated a minimum value for CO at an inlet pressure around 0.52 MPa at 1426 K and 0.62 MPa at 1539 K.

Exit Flow Angle

A characteristic design feature of the VAB combustor is the swirl vanes located in the swirl channel inlet. The swirled inlet airflow concept is not new and has been proven beneficial for good overall combustor performance. This VAB combustor incorporated the swirl concept similar to that described in reference 11. Markowski and Lohmann reported that this swirl concept gave the combustor "excellent stability characteristics and moderate total pressure losses. The concept of piloted combustion in a centrifugal force field under conditions comparable to those in an aircraft turbine engine has been demonstrated and produced high heat release rates and combustion efficiency." They analytically derived that the best swirl angle would be 60 degrees. Solar also conducted some experiments on swirl angle[5], and found the optimum to be a 60 degree swirl vane angle in the VAB combustor inlet. Since it was of interest to determine how well swirl angle was maintained throughout the combustor, a yaw probe was used for making exit angle measurements at two conditions.

Results of the exit angle survey at isothermal and burning conditions are given in figure 9. At isothermal conditions, the average swirl angle was 47 degrees at three different inlet pressures. The overall average exit angle varied by radial location and not inlet pressure. The tangential component of velocity decreases with increasing combustor radius to conserve angular momentum. Consequently the swirl angle is less at the exit than at the inlet because the exit has a larger radius. At burning conditions the swirl angle decreased to an average of 23 degrees and was more radially uniform across the exit plane. Also, as heat addition was increased in the combustor, the axial velocity component increased and thus reduced the swirl angle.

Summary of Results

The lean premixed VAB annular combustor demonstrated the capability to produce excellent combustor performance and low level exhaust gas emissions at inlet pressures up to 0.83 MPa. Additional conclusions from this experiment are:

1. Measured temperatures showed minimal radial deviation of measured temperatures at the combustor exit. Pattern factors were consistently between 0.16 and 0.20 exhibiting very uniform mixing and exit temperature profiles.

2. Maximum oxides of nitrogen were 1.05 gm NO_2/kg fuel at the highest inlet pressure (0.83 MPa) and exit temperature (1539 K) tested. At these same conditions carbon monoxide and unburned hydrocarbons were 2.56 gm CO/kg fuel and 0.85 gm UHC/kg fuel, respectively. The CO and UHC emissions were slightly higher (less than 2.5 percent) than the gaseous emissions produced by Solar's tests at 0.10 MPa and equivalent exit temperatures.

3. A combustor swirl angle exit survey revealed that the exit swirl angle was a nominal 47 degrees at isothermal conditions and 23 degrees at burning conditions.

4. Previous correlations have related NO_x proportionally to the combustor inlet pressure raised to some exponent. In this experiment, the pressure exponents were between 0.5 to 1.0 for fuel-air ratios from 0.023 to 0.027. A precise pressure exponent could not be determined from this experiment due to the limited number of data points.

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TABLE I. - A COMPARISON OF THE FULL ANNULAR VAB COMBUSTOR EMISSION INDICES

[Emission index = GM pollutant/kg fuel]

Exhaust gas emission at given exit temperature	Solar (ref. 8)	NASA Lewis		
	Pin = 0.10 MPa	Pin = 0.52 MPa	Pin = 0.62 MPa	Pin = 0.83 MPa
NO_x at 1424 K	0.10	0.29	0.32	0.36
NO_x at 1539 K	.25	[a].72	.96	1.05
CO at 1426 K	23.50	6.66	8.92	12.40
CO at 1539 K	2.50	[a]2.25	1.86	2.56
UHC at 1424 K	12.50	8.90	5.42	5.27
UHC at 1539 K	.84	[a]1.91	.94	.85

[a]T_{exit} = 1503 K.

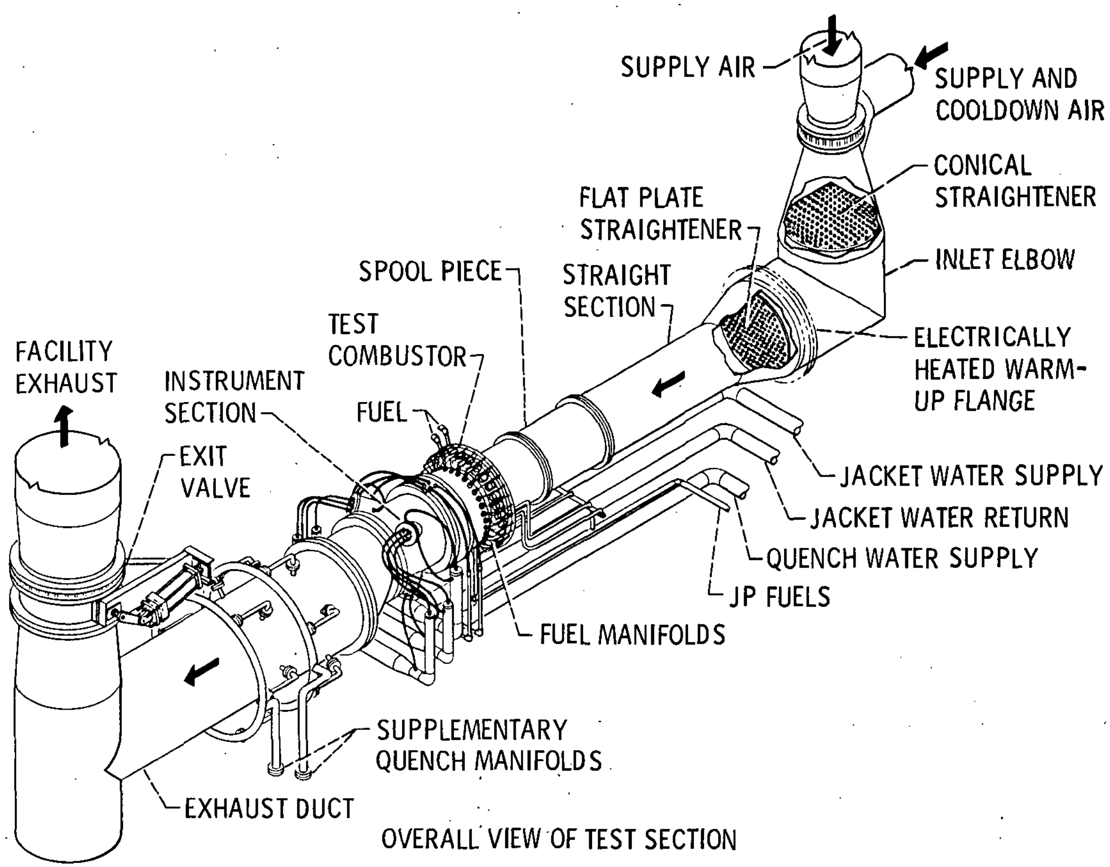

Figure 1. - Test facility in the Engine Components Research Laboratory.

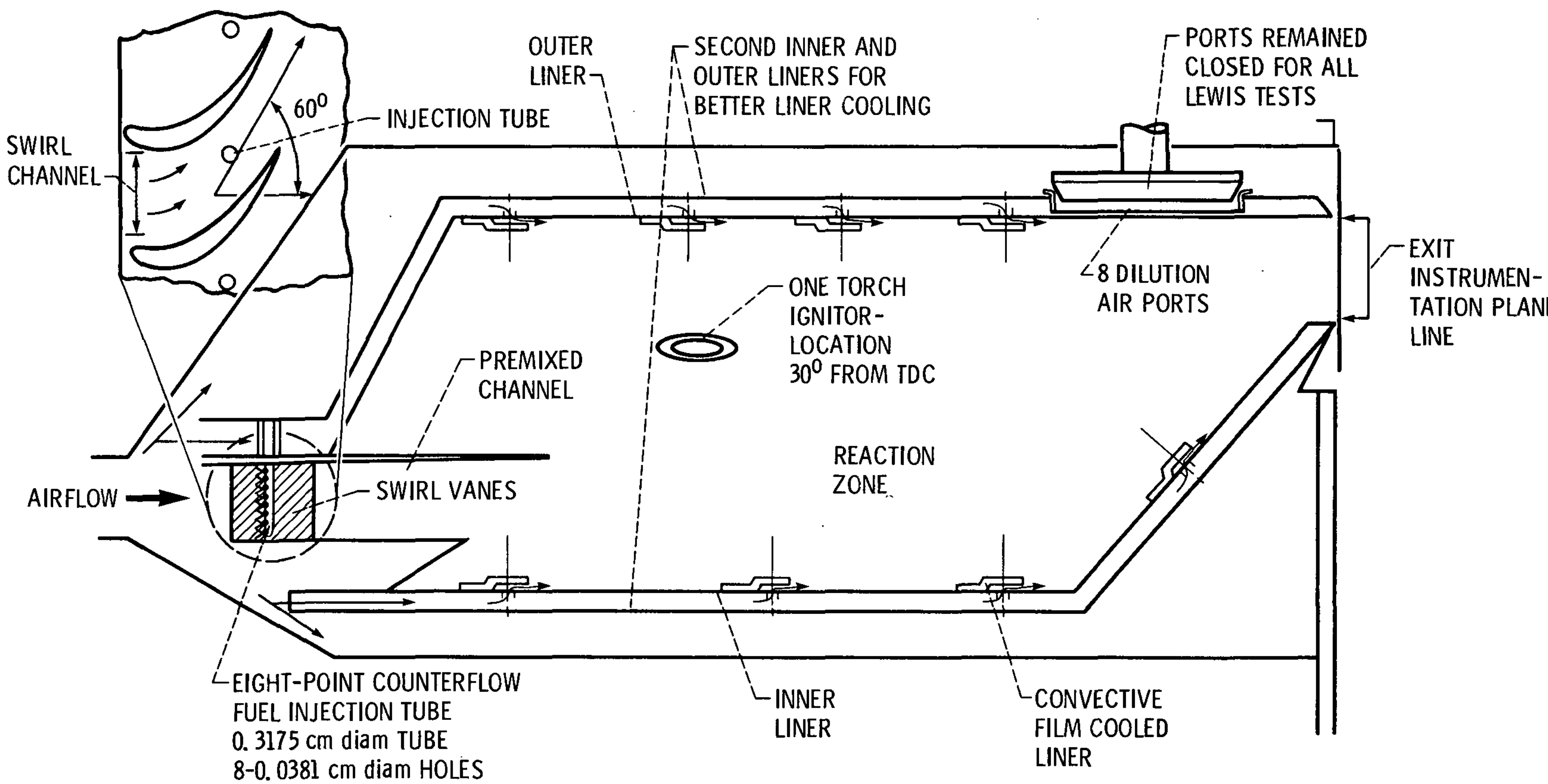

Figure 2. - Cross-section of the vortex airblast (VAB) combustor.

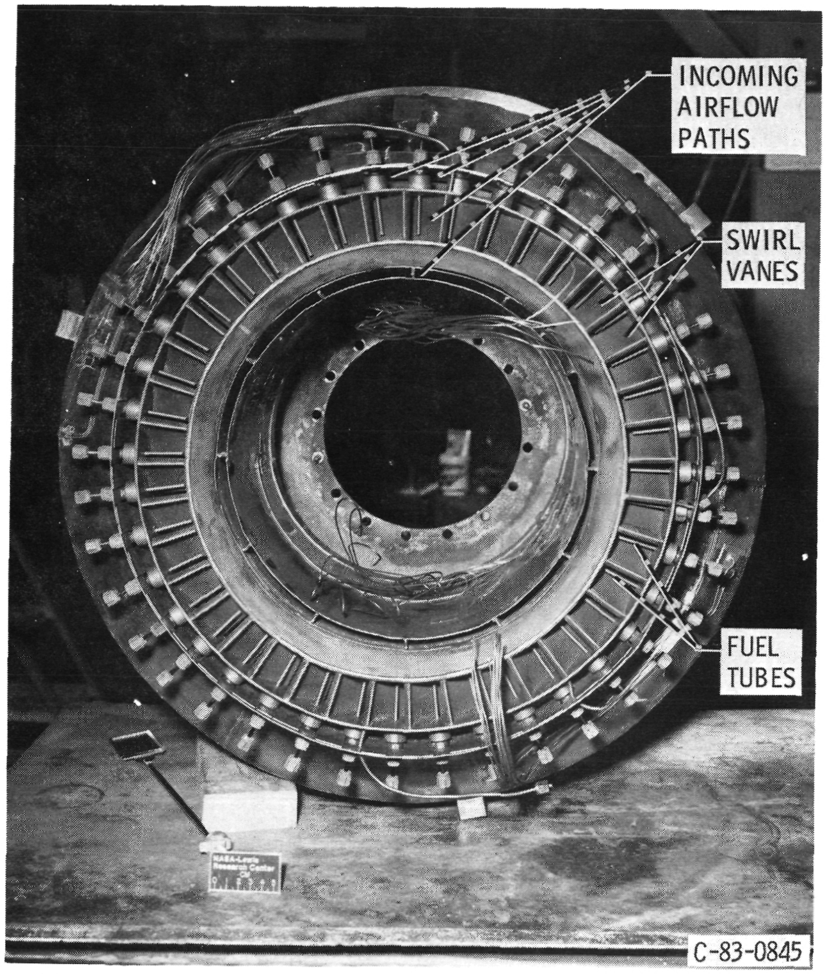

Figure 3. - Photograph of the VAB combustor looking downstream at the inlet swirl vanes and fuel injection tubes.

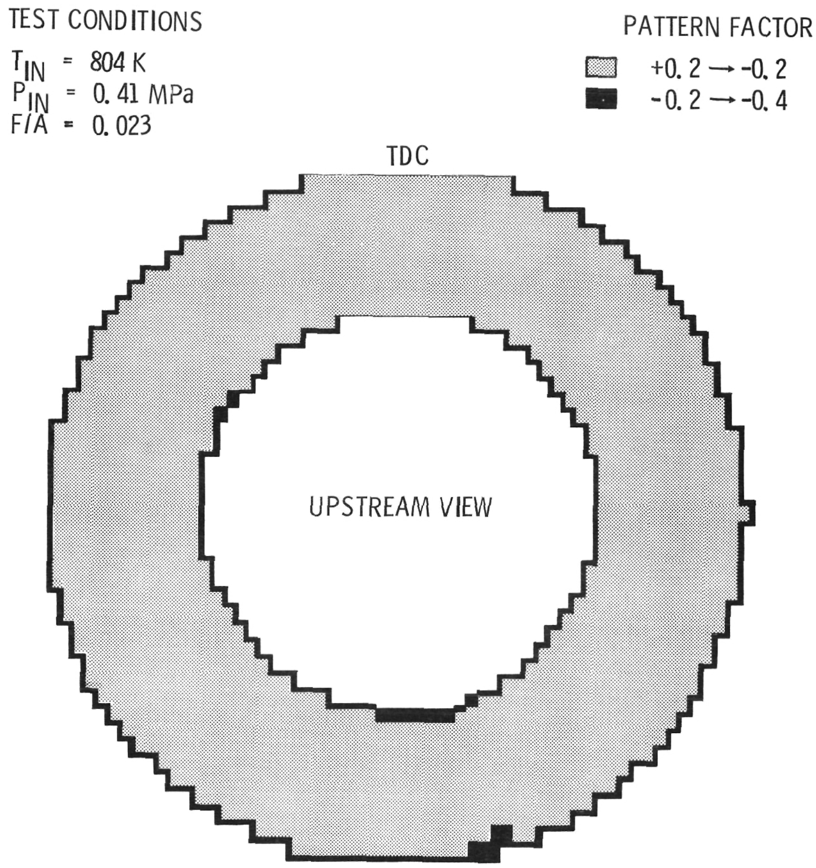

Figure 4. - A representation of the pattern factor observed on the CRT located in the control room.

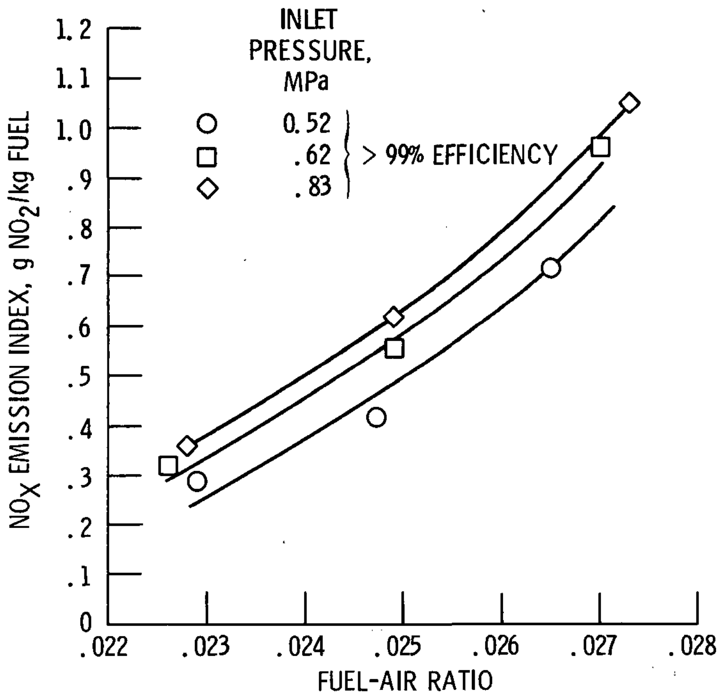

Figure 5. - Oxides of nitrogen as a function of fuel-air ratio at various inlet pressures. Inlet temperature, 703 K.

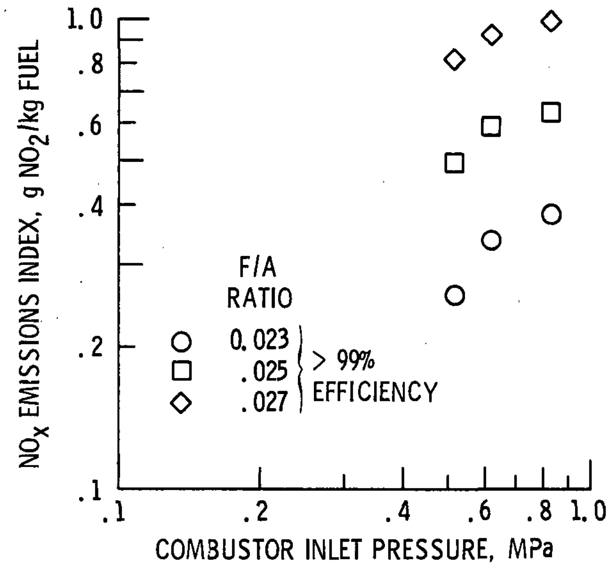

Figure 6. - NO_X emission index as a function of inlet pressure at three fuel-air ratio values. Inlet temperature, 703 K.

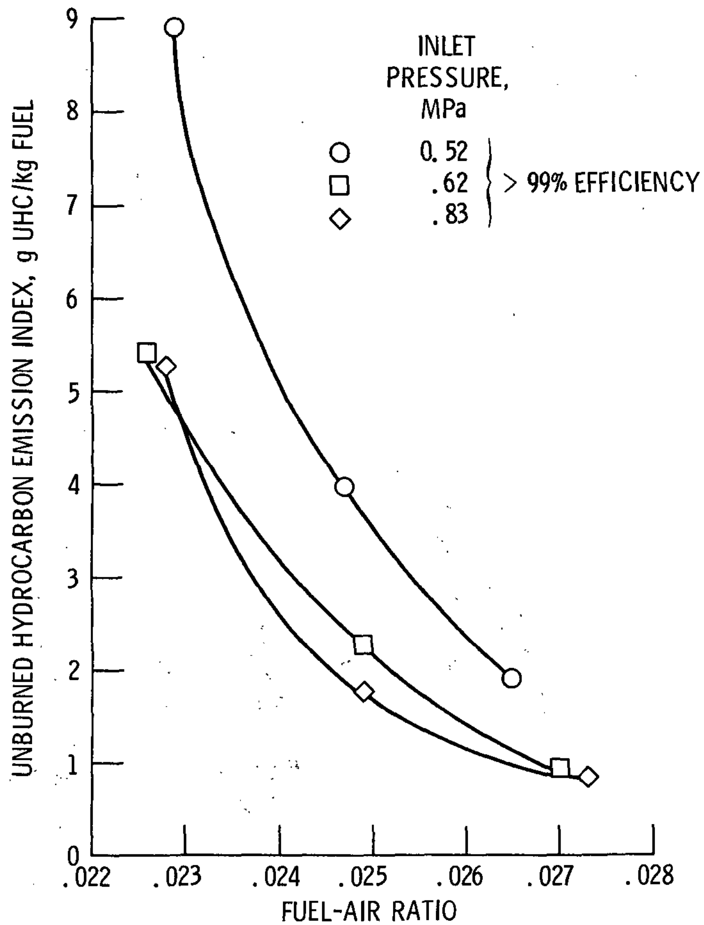

Figure 7. - Unburned hydrocarbons emissions as a function of fuel-air ratios at various inlet pressures. Inlet temperature, 703 K.

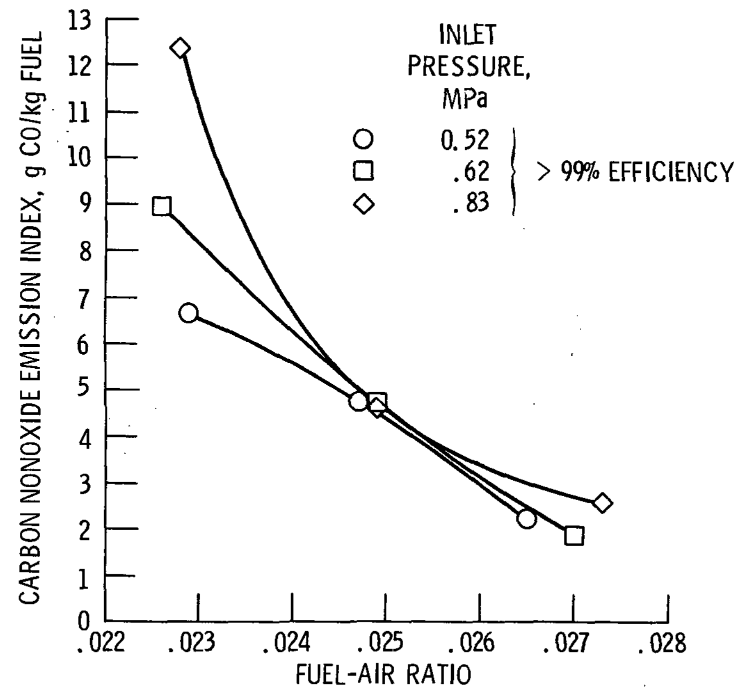

Figure 8. - Carbon monoxide emissions as a function of fuel-air ratios at various inlet pressures. Inlet temperature, 703 K.

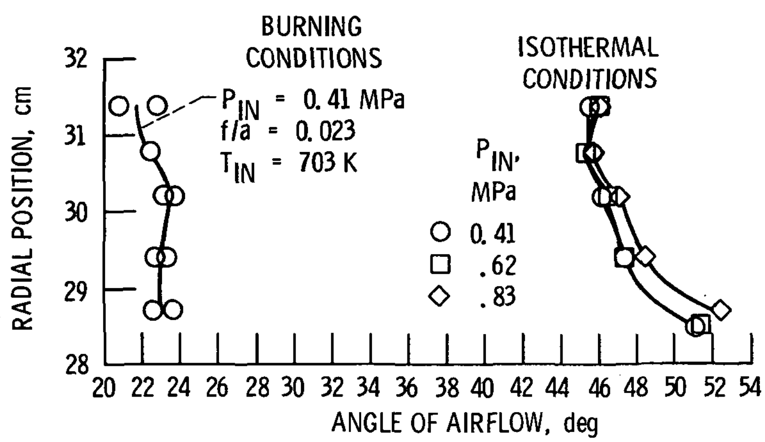

Figure 9. - Exit plane swirl angles for isothermal and burning conditions.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-83615		

4. Title and Subtitle
Experimental Investigation of the Low NO_x Vortex Airblast Annular Combustor

5. Report Date

6. Performing Organization Code
533-04-1D

7. Author(s)
S. M. Johnson, J. A. Biaglow, and J. M. Smith

8. Performing Organization Report No.
E-2046

10. Work Unit No.

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Memorandum

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared for the Twentieth Joint Propulsion Conference cosponsored by the AIAA, ASME, and SAE, Cincinnati, Ohio, June 11-13, 1984

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Combustor; Oxides of nitrogen: Emission indices; Annular combustor; Lean premixed combustor; Pattern factors	Unclassified - unlimited STAR Category 07

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified		

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